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Design and implementation of high magnification framing camera for NIF "ARIANE Light"

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Abstract

Gated X-Ray imagers have been used on many ICF experiments around the world for time resolved imaging of the target implosions. ARIANE (Active Readout In A Neutron Environment) has been developed for use in the National Ignition Facility and has been deployed in multiple phases. Phase 1 (complete) known as ARIANE Ultra Light (Alignment proof of concept), Phase 2a known as ARIANE Light (complete) (X-ray gated detector with electronic recording), Phase 2b (complete) (X-ray gated detector with film recording) and Phase 3 known as ARIANE Heavy which is currently under development. The ARIANE diagnostic is comprised of the following subsystems: pinhole imaging system, filtering, detector head, detector head electronics, control electronics, CCD, and film recording systems. The phased approach allows incremental increases in tolerance to neutron yield. Phase 2a and 2b have been fielded successfully and captured gated implosion images on CCD and film at yields up to 7×10^{14}. As the yields in the NIF increase Phase 3 will be a longer term solution incorporating indirect optical path, improved hardened advanced detectors and significant (tons) of shielding. Design and Initial commissioning data for Phase 1-2b are presented here.

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Introduction

Time gated x-ray imaging [1] is essential for the National Ignition Campaign (NIC) [2] which is currently underway at the National Ignition Facility (NIF) [3]. Time gated imaging provides temporally resolved images that are used for measuring shape, size and burn history of an imploding cryogenic deuterium-tritium (DT) capsule as it is compressed during Inertial Confinement Fusion (ICF). Studying the symmetry and the fuel size during implosion are two key parameters used to optimize tuning experiments of the NIC [2,3]. As the yields increase new designs for time resolved x-ray imaging systems are required. The most common of these are pinhole array framing cameras that consist of a pinhole array that produces a large number of x-ray images onto a micro channel plate (MCP). The temporal gating of the MCP allows the x-ray images to be captured at different times allowing a reconstruction into a movie of the target shape size and burn history over a 1 ns time scale. The x-rays are converted to electrons in the MCP. The resulting cascade of electrons are accelerated through the MCP and multiplied to a high order [4,5]. After exiting the MCP the electrons are converted to visible photons from the phosphor coating on the fiber optic face plate. The photons are transmitted through the fiber optic face plate for recording onto an electronic CCD readout or film (Figure 1).

Table 1. Design Summary Table

ARIANE Subsystems and relative position from TCC						
TCC ⌖	Pinhole Location	FIP1	FW	FIP2	FIP3	Detector Plane
0 cm	27 cm	6.22 m	6.55 m	6.88 m	6.97	7.1 m
ARIANE Detector Details						
IP	MCP	Fiber Optic	CCD	Film		
FUGI BAS-IP MS 2040	8° Bias, Gold Coated	6 micron fiber, fused silica	Spectral Instruments SI-1000	TMAX3200		

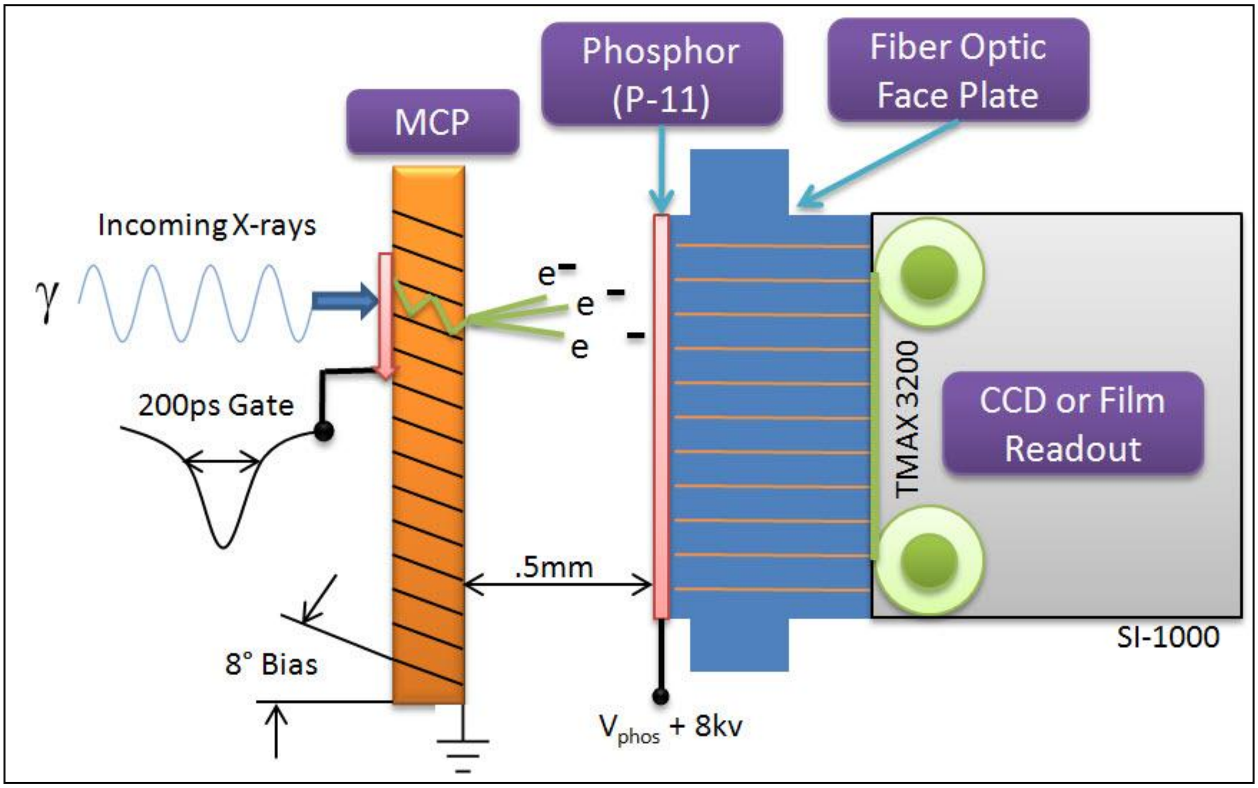

Figure 1. MCP used to amplify secondary electrons ejected by x-rays incident on a gold photocathode strip. A voltage pulse on the strips provides a time dependent gain that gates the signal. Electrons from the MCP are proximity-focused on a phosphor screen and the image is relayed through the fiber block onto CCD or film [7].

Other gated x-ray detectors (GXD) currently used on NIF are capable of capturing data at DT neutron yields up to Y_n~ 10^{13} at a standoff distance of 1.3 m from target chamber center (TCC). At the same standoff distance and switching from CCD to film readout (HGXI), a slight improvement is realized with the ability to capture data at yields up to Y_n~ 10^{15} [6]. At yields beyond this level the neutron-induced noise becomes too high for imaging with the CCD (GXD). To keep up with the increase in target yield new x-ray diagnostics are required with increased radiation hardness. A next generation x-ray diagnostic ARIANE has been designed to operate at DT neutron yields up to Y_n~ 10^{16} and is currently fielded on the NIF. As an x-ray framing camera ARIANE functions just like an HGXI or GXD, but is able to operate at higher yields due to an improved head design and the increased detector distance from TCC. ARIANE consists of a pinhole array positioned at 27 cm from

TCC supported on an adjacent Diagnostic Manipulator (DIM). The ARIANE detector is placed outside the target chamber (Port 90/89), 7 m from TCC, rotated 11° on the equator from the DIM (Port 90/78) (Figure 2). The resultant magnification of ARIANE is 25x.

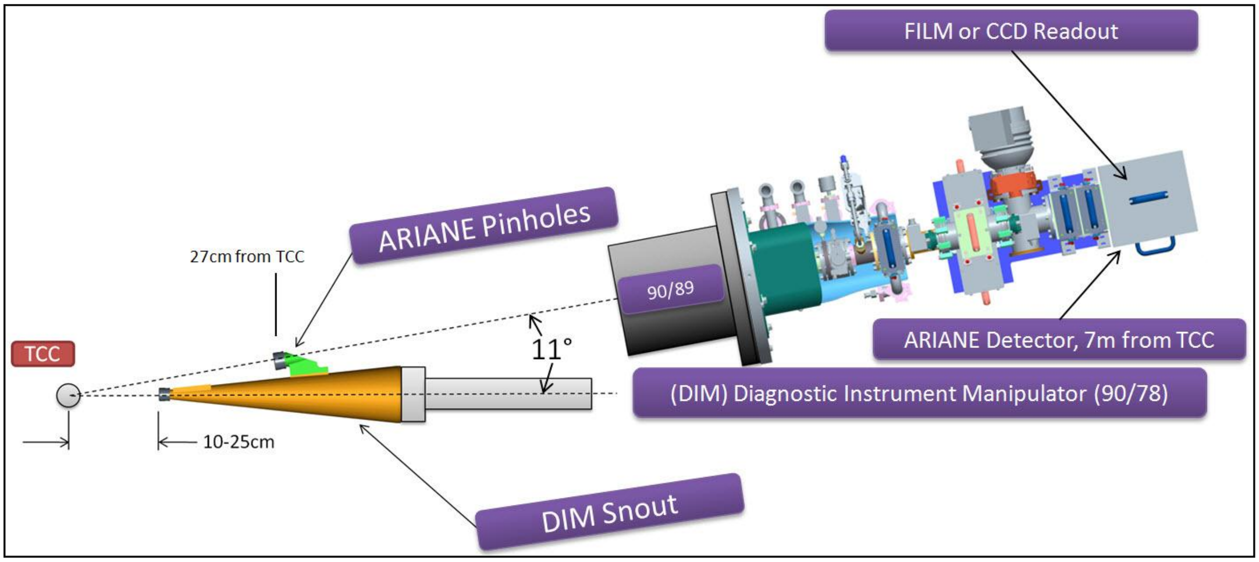

Figure 2. Plan view of ARIANE x-ray imaging configuration, pinholes placed at 27 cm from TCC supported by the DIM and the MCP and phosphor outside the TC at 7 m from TCC.

ARIANE has been deployed in three major phases. Phase 1, ARIANE Ultra Light, was an alignment proof of concept. Phase 2a, ARIANE Light was an x-ray gated detector with electronic recording. Phase 2b was an x-ray gated detector with film recording. Phase 3, ARIANE Heavy, is still currently under development. Phases 1, 2a and 2b have been completed with 2b in operation presently.

ARIANE, Phase 1 (Alignment Proof of Concept)

Phase 1 of ARIANE was used to validate the pointing and alignment capability using the DIM 90-78 mounted ARIANE pinhole system. The first step of the process was to develop a detailed error budget including manufacturing tolerances, assembly tolerances, and positional and alignment capabilities of the DIM positioning systems. To hold the pinholes for ARIANE a new cone design was required that could accept a pinhole array mounted off axis of the DIM 90-78 and aligned precisely at the 90/89 port (11° off axis). The ARIANE pinhole mount is an appendage attached to a specially designed DIM cone (Figure 3). The ARIANE pinhole alignment and position is driven by the DIM 90-78 primary diagnostic on the 90/78, not ARIANE. Since ARIANE is not on the DIM axis the pinhole array was sized to accommodate positioning and alignment to always place images on the MCP detector. Using the error budget as a guide the first set of ARIANE Ultra Light (AUL) pinholes deployed covered a 9.5mm diameter pattern. Using fiducials built into the pinhole array the images collected on image plate were used to determine alignment repeatability of the system [±0.5 mm] and the final size of the pinhole array needed for normal operation. Multiple cone designs were created to allow participation of ARIANE simultaneously with either GXD or HGXI configuration. The position of the pinhole mount to the cone, once assembled, was validated using CMM prior to commissioning to ensure it adhered to the prescribed alignment budget.

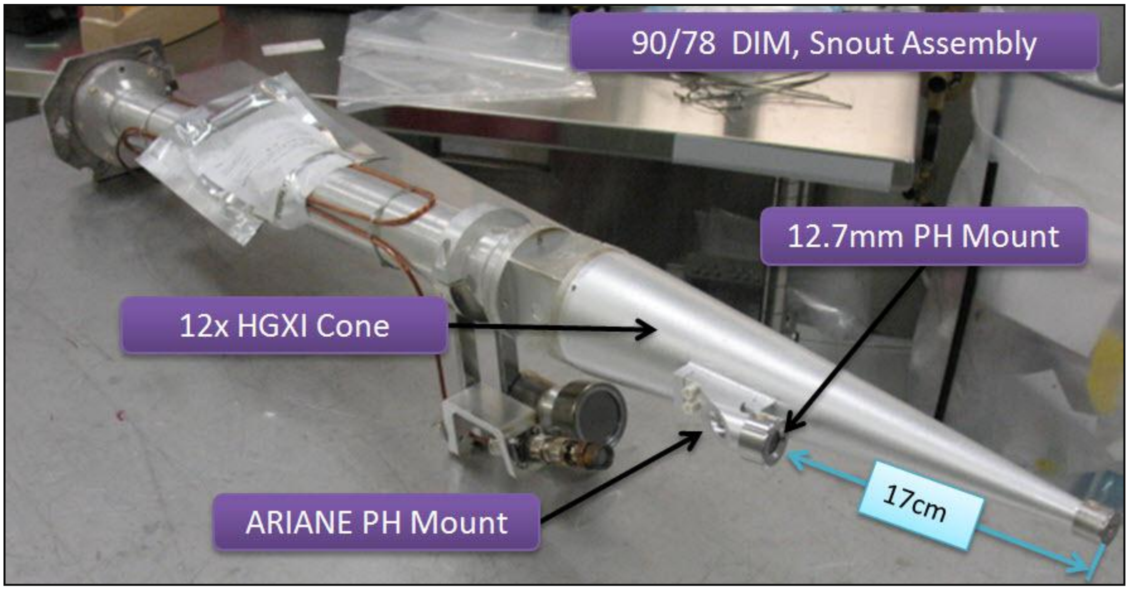

Figure 3. ARIANE DIM cone with 12.7 mm pinhole mount attached to the side with line of site port 90/89. Pinhole placed at 27cm from TCC.

The first phase of the ARIANE hardware included installation of a target chamber port reducer, isolation gate valve and a Filter Image Plate vessel (FIP) (Figure 4 and Figure 5). The inside of the FIP vessel is designed to hold an aluminum frame to hold filter materials or image plate (Figure 6). The limiting aperture of the system was the internal diameter of the port which is 60 mm. The image plate extended slightly beyond the ID to ensure the full array of images that were viewable was recorded.

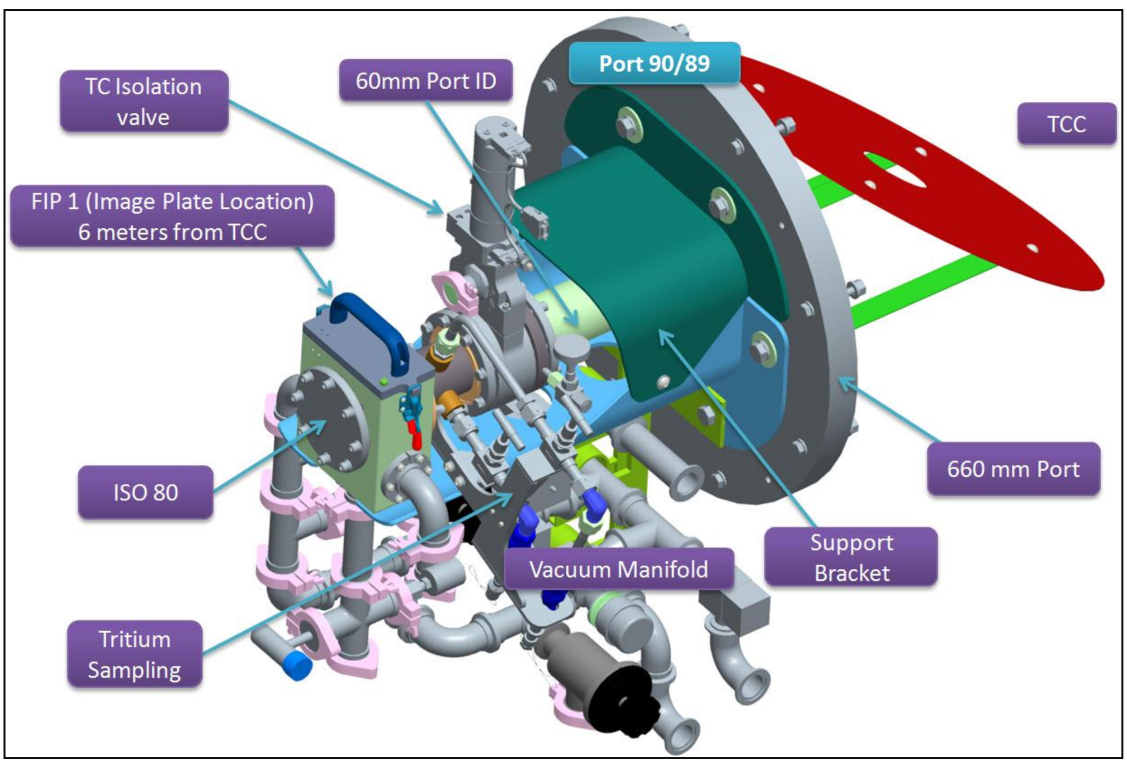

Figure 4. ARIANE Ultra Light 3D model general arrangement.

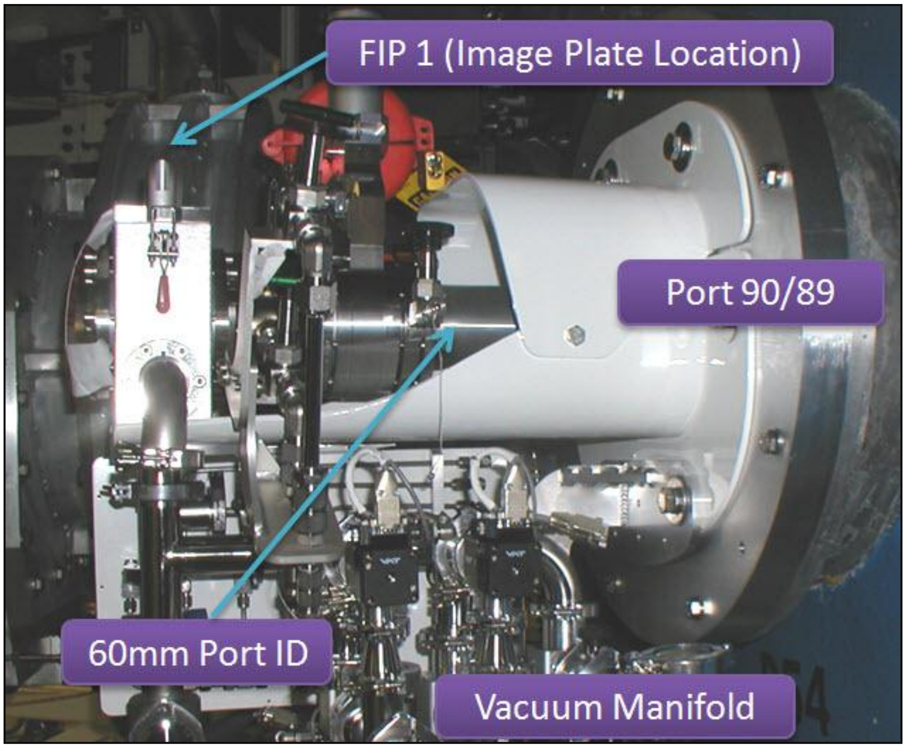

Figure 5. Phase 1, ARIANE Ultra Light (AUL) fitted to the NIF target chamber.

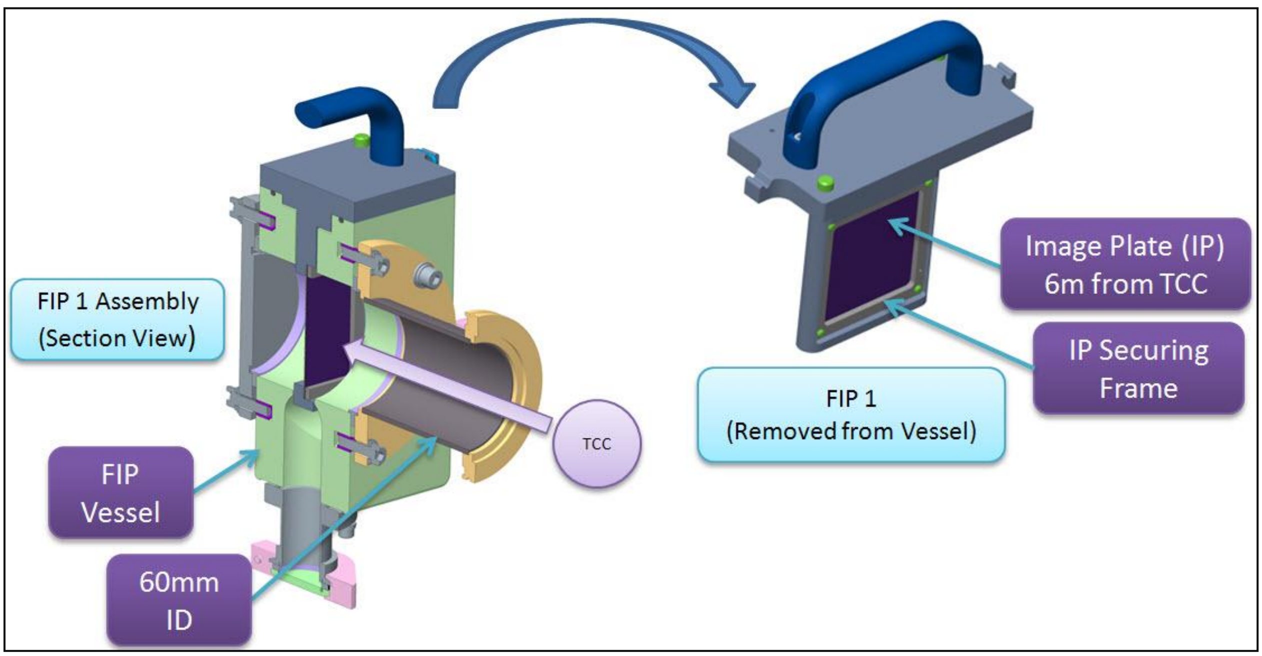

Figure 6. Phase 1, ARIANE Ultra Light (AUL) fitted to the NIF target chamber.

AUL successfully collected alignment data on the first shot participation and every shot thereafter. The pinhole array has now been reduced from a 9.5 mm round pattern to 4.5 mm using the information provided by the alignment pinhole experiments. Time-integrated core images at peak compression, used to verify ARIANE's alignment are shown in Figure 7. Due to the large magnification, the alignment and positioning of the image plate was easily achieved. The FIP was located within ±0.5 mm of its intended location, the equivalent of ±20 um at the plane of the pinhole array. With the alignment proven the next phase of ARIANE Light was approved.

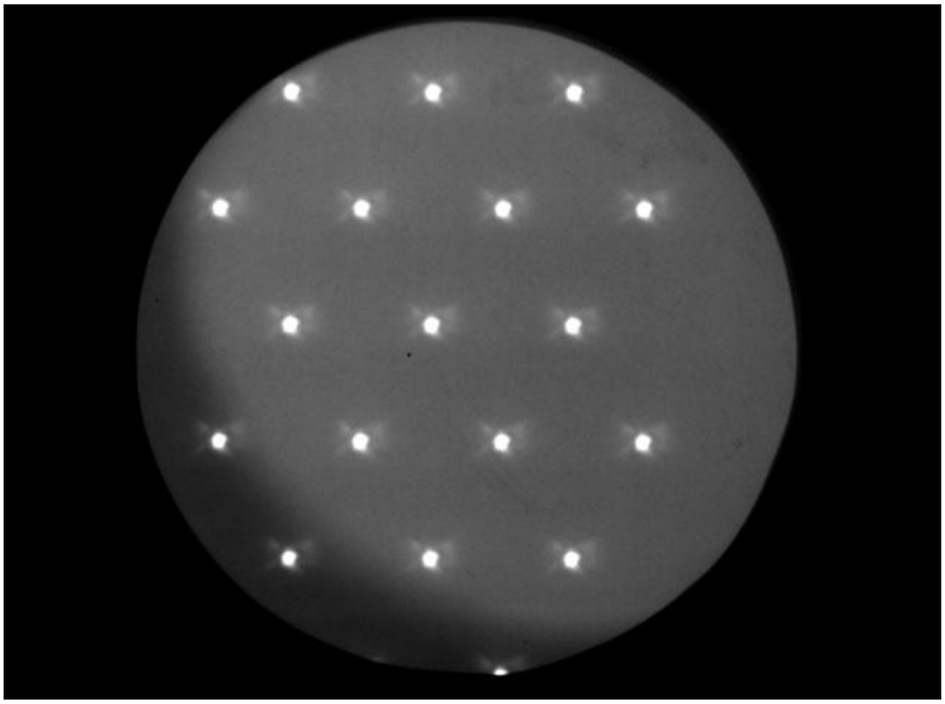

Figure 7. Typical alignment images captured on Image Plate (IP) at FIP1.

ARIANE, Phase 2 (ARIANE Light)

To implement Phase 2, the AUL hardware was left intact and additional equipment added to expand to the ARIANE light (Figure 8). This included an automated filter wheel system, dedicated high vacuum system, two additional FIP locations, gated detector in an EMI enclosure and electronic CCD readout interchangeable with film. Alignment of the support hardware for the detector was achieved using a laser tracker survey system and positioned to within ±0.5 mm. Alignment precision of the detector is eased by the high magnification and the pinhole array overfill on the detector plane mitigating any DIM or ARIANE misalignment.

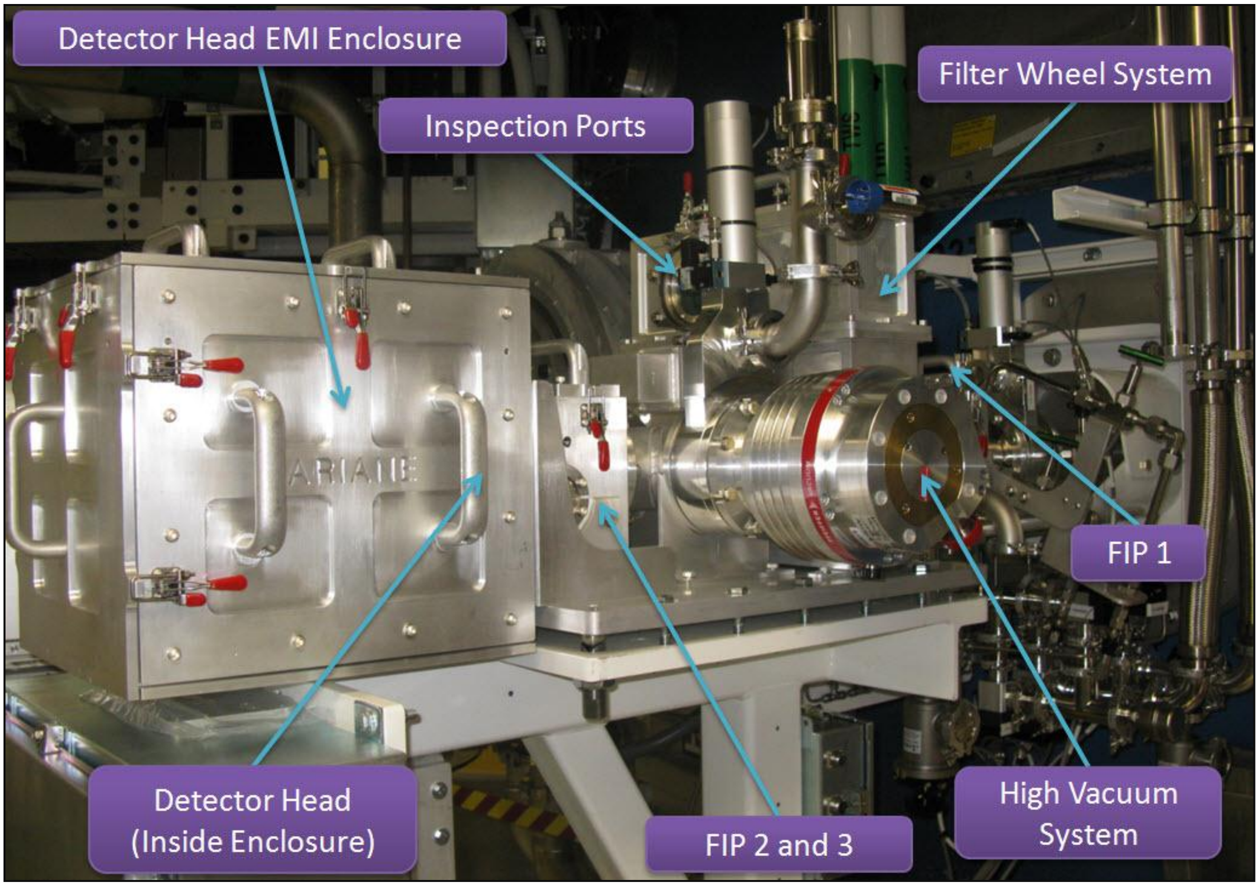

Figure 8. ARIANE Light system overview, Mounted on NIF Target Chamber.

To limit radiation exposure to personnel an automated filter wheel system was added that is controlled remotely through the NIF ICCS system (Figure 9). The filter wheel system includes two filter wheels, six positions each. The 12 locations are loaded with an array of filter thicknesses allowing remotely selectable filtering options. The filter wheels are powered by radiation hardened stepper motors through 25:1 harmonic drives. Harmonic drives were chosen for their compact design, zero backlash, and high torque capability in a small package. The filter wheel indexing is readout through the motor step counts and magnetic read switches at each location. Other features include optical viewing windows to check filters for damage and verification that the system has been advanced to the desired selection. Each viewport is fitted with KG5 laser safety glass to mitigate TC laser hazards and Parker Chromerics Division 100 opening per inch carbon black EMI mesh to contain EMI fields generated by the HV pulse across the MCP.

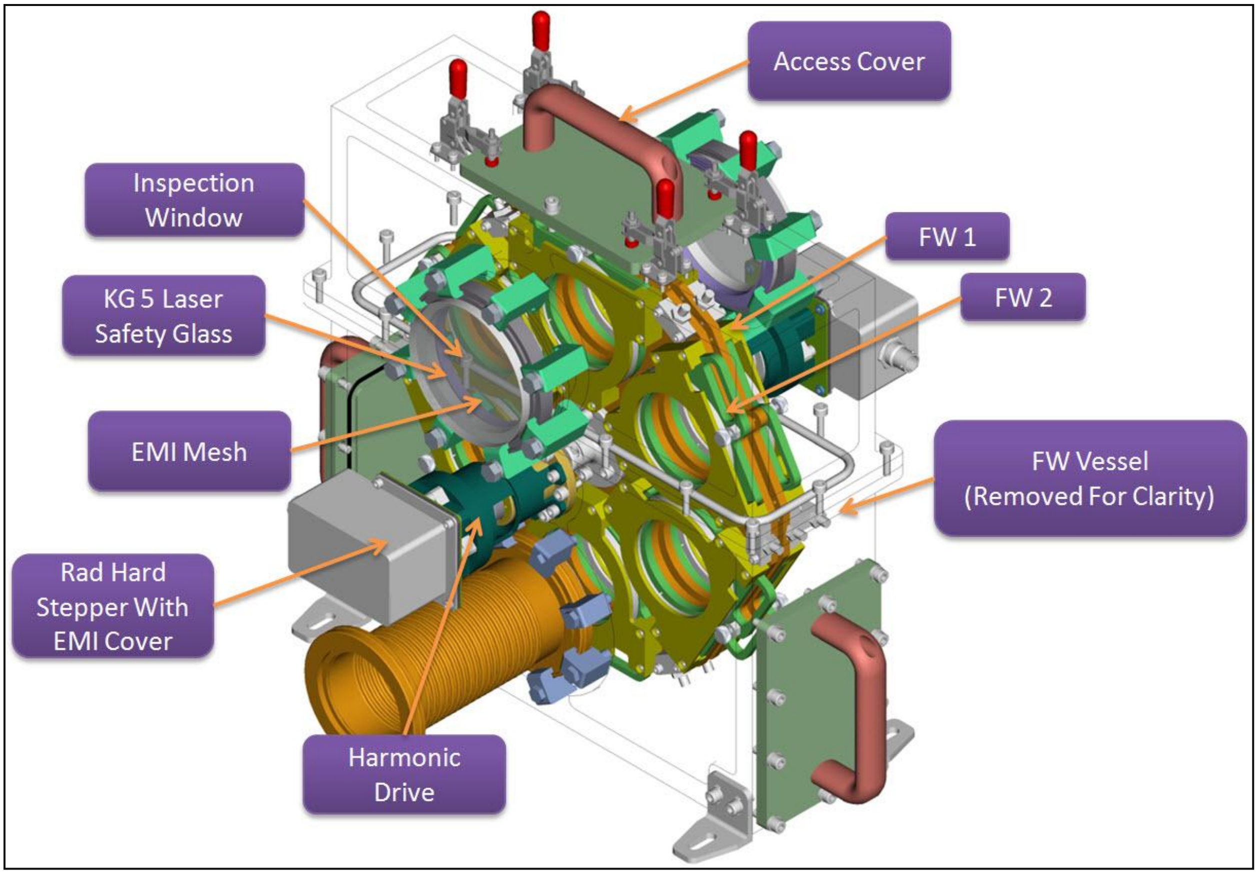

Figure 9. ARIANE automated filter wheel system, remotely selectable by the NIF ICCS system.

In front of the detector two additional FIP locations were added, one location dedicated to hold black Kapton to provide a dark environment when film is used for data collection.

To mitigate arcing when the MCP is pulsed (designed to operate with 10kv pulse) ARIANE requires a base pressure better than 5 x 10^{-5} torr and is fitted with its own high-vac system with molecular turbo pump. The high vacuum system allows the channel plate to stay under vacuum (normal operation < 5 x 10^{-5} torr) at all times to prevent damage from water absorption.

The detector head itself is an upgrade from gated x-ray detector GXD [1]. Improvements and modifications that were included in the ARIANE design:

- Body and wings 3 separate pieces, 1/3 the cost of previous head designs
- Shortened wings for the 250 ps pulse.
- Body made of 30% glass filled PEEK, serves as insulator for HV feed-throughs
- Improved phosphor “vampire contacts on fiber optic”.
- Designed for 10 KV pulsed Phosphor (P-11). (GXD was using 5 KV).
- Compatibility with commercially available 120 mm Hasselblad film back.
- Improved phosphor vacuum feed-though.
- Lemo connectors and contained phosphor slow down boxes, with monitor.

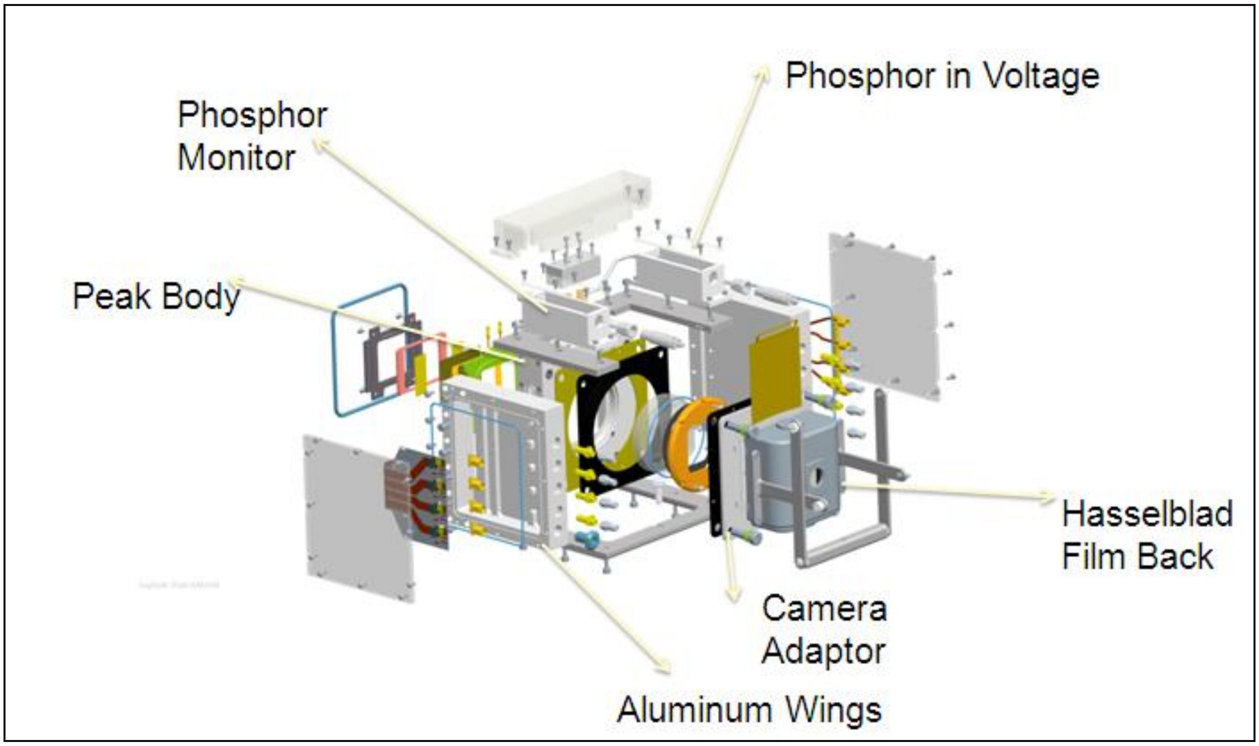

Figure 10. ARIANE DH Overview, shown with Hasselblad filmback.

When the signal to noise background levels increased as the yield increased, the CCD camera was replaced with a commercial Hasselblad film back. Key benefits to the Hasselblad unit are its reliability. The filmback itself is left completely as a stock commercial component and adapted to the ARIANE detector head (DH) using factory Hasselblad adapter plates and a custom light baffle design to allow the film to be preloaded against the face plate, then pulled back away from the face plate for insertion of the dark slide. One additional benefit that is included is the integrated interlock that disables the removal of the filmback without the dark slide in place.

Challenges

The deployment of ARIANE on the NIF brought about a few new challenges. (1) ARIANE was the first x-ray imaging diagnostic to be placed outside the TC volume imaged through a set of pinholes held off-axis of a diagnostic manipulator (DIM). This required the plane of the pinholes to be within 0.5° of the 90/89 port axis. DIM alignment accuracy was mitigated by increasing the overall size of the pinhole array to ensure full coverage at the detector plane. To cover all alignment uncertainties the pinhole array was increased from 1.4 mm diameter (minimum for perfect alignment) to 4.5 mm, a total of 203 pinholes. This ensured full coverage of the detector plane with images.

The second challenge was coming up with a method of increasing the number of images captured on the MCP. With the relatively high 25x magnification and the existing three part stack design of collimator-pinhole-collimator results in as few as 3 to 4 images on an MCP strip. (Figure 11 and Figure 12)

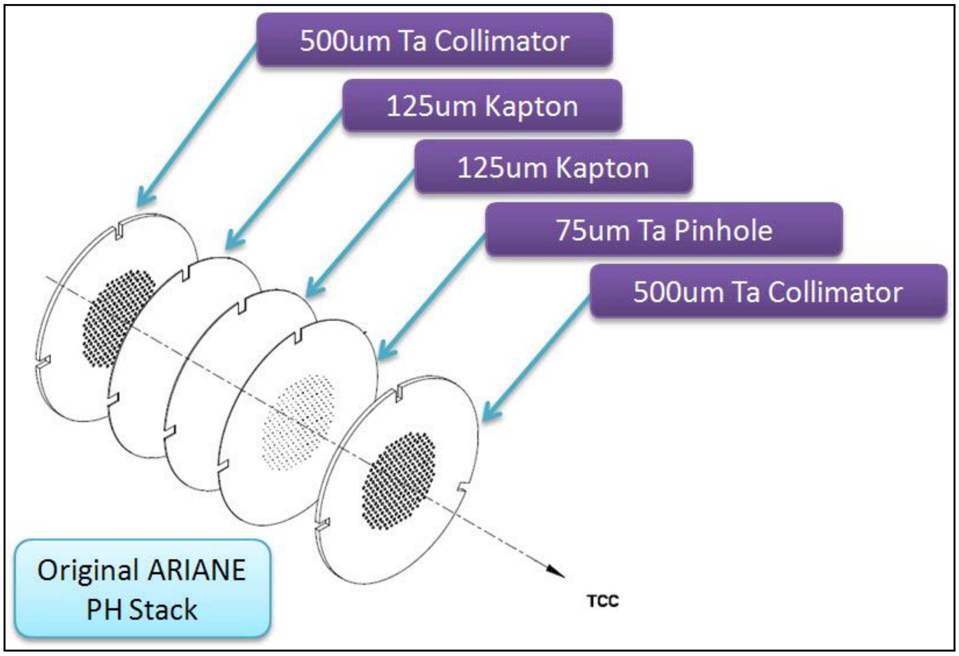

Figure 11. Original ARIANE pinhole configuration, typical for NIF pinhole framing cameras

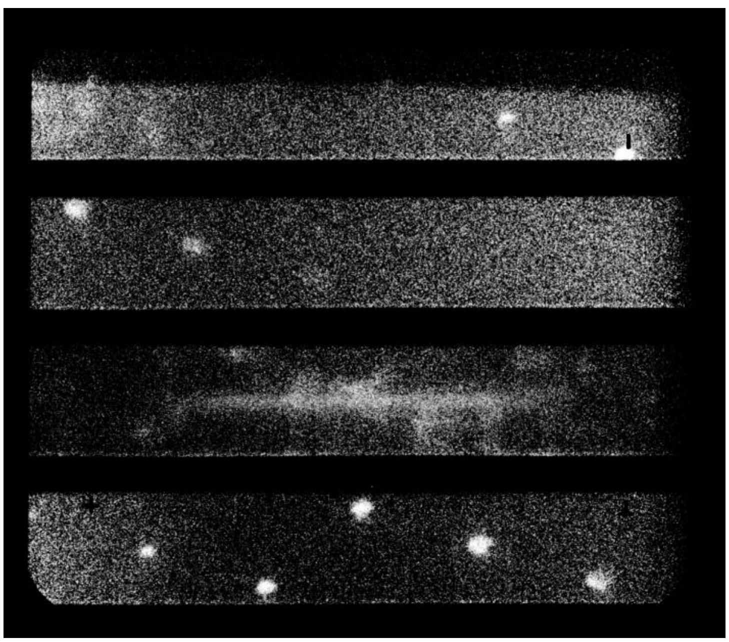
Figure 12. Typical images taken on CCD with original ARIANE pinhole configuration

The limiting factor to achieve more images is the collimator manufacture spacing. As the 150 um collimator holes get closer the landing between holes becomes too small to handle the heat load generated during laser drilling, melting the landing between holes. The previous ARIANE pinholes were 10 um in diameter on a 75 um thick Tantalum and the collimator holes were150 um diameter on 500 um Tantalum.

By combining the collimators and pinholes onto two parts and by alternating pinholes and collimators [flip flopping] the spacing was reduced, increasing images to 8-9 per strip. The collimator thickness was reduced to 200 um. The pinholes remained the same size and fit between the collimators. Manufacture costs were reduced due to part tolerances and reduced parts, see Figure 13 and Figure 14.

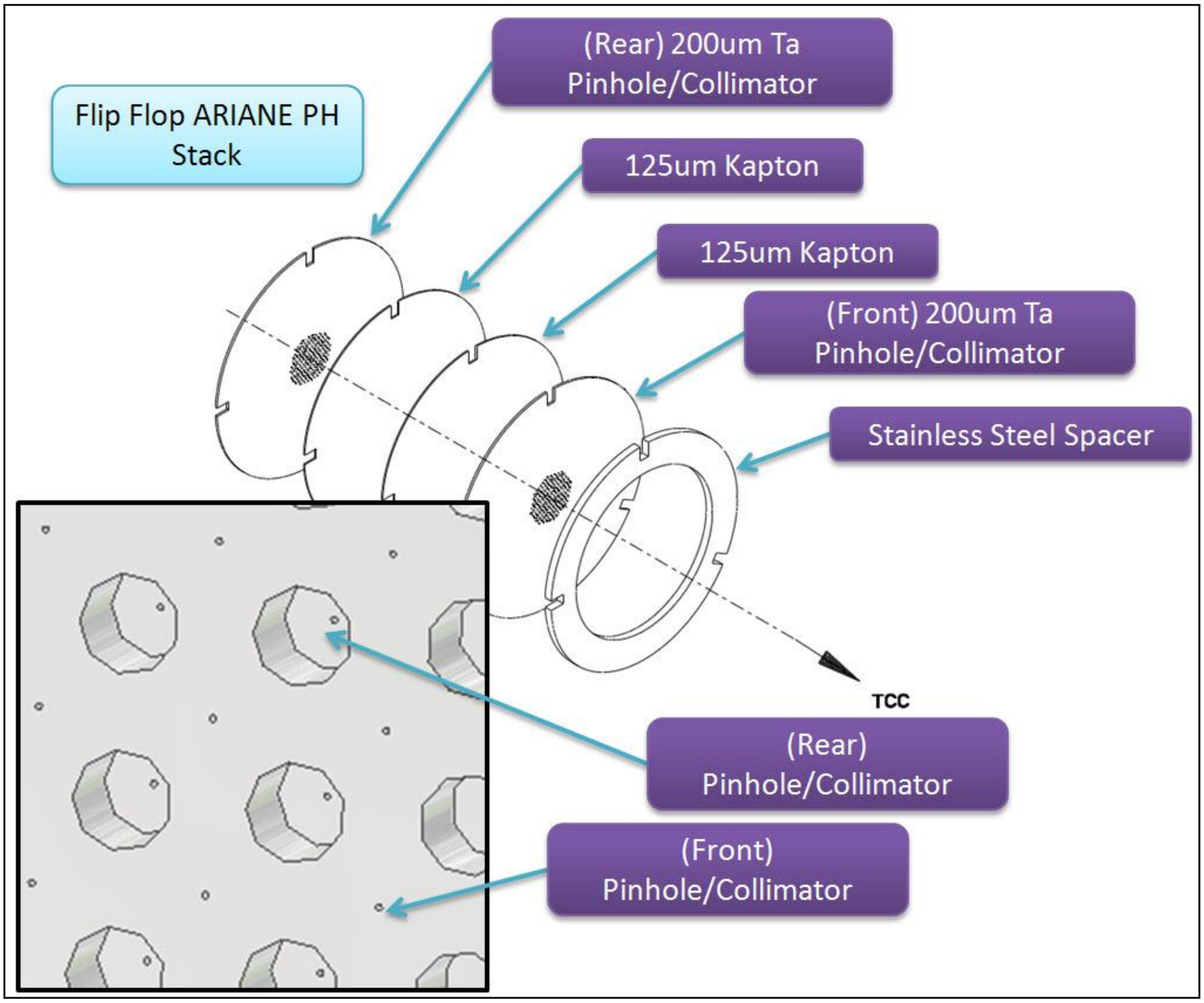

Figure 13. Flip Flop Pinholes on two alternating Collimator/Pinhole parts.

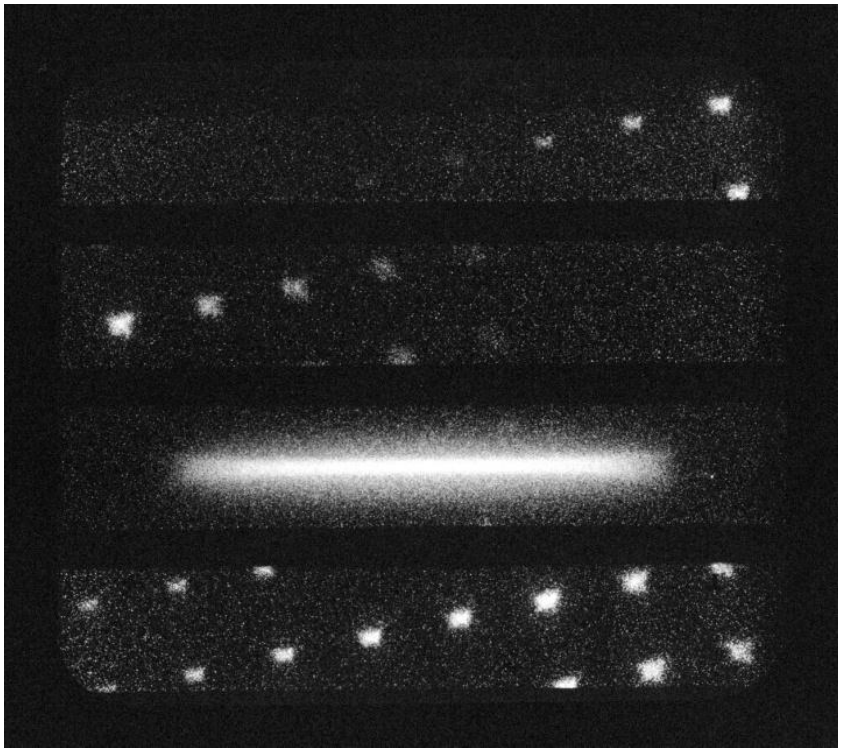

Figure 14.Typical images taken on film with alternating Flip Flop Pinhole configuration

A third challenge was the asymmetric loading caused by the addition of the side mounted pinhole set This asymmetric debris wind load required FEA analysis to ensure structural integrity at 2.0 MJ of laser energy. Changes to the structural supports were made to accommodate the higher side loads.

Summary

ARIANE Light has been performance qualified and has been operational since December 2011. ARIANE has proven to be a reliable X-ray framing camera on the NIF and has provided quality imaging to help direct the NIC effort. A second ARIANE detector head is under calibration testing at NStech, Livermore, CA. as a spare. Currently ARIANE is configured with film. The CCD camera may be re-installed as required for upcoming shot campaigns. Phase 3 ARIANE design activities continue.

References

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